MAGNETIC ACTIVITY IN STELLAR MERGER PRODUCTS

Noam Soker[1] and Romuald Tylenda[2]

ABSTRACT

We study the expected X-ray luminosity of stellar merger products several years after merger. The X-ray emission is assumed to result from magnetic activity. The extended envelope of the merger product possesses a large convective region and it is expected to rotate fast. The rotation and convection might give rise to an efficient dynamo operation, therefore we expect strong magnetic activity. Using well known relations connecting magnetic activity and X-ray luminosity in other types of magnetically active stars, we estimate that the strong X-ray luminosity will start several years after merger, will reach a maximum of $L_x \sim 3 \times 10^{30}$ erg s^{-1}, and will slowly decline on a time scale of ~ 100 yr. We predict that X-ray emission from V838 Mon which erupted in 2002 will be detected in 2008 with 20 hours of observation.

Subject headings: stars: supergiants – stars: main sequence – stars: binary – stars: individual: V838 Mon – stars: magnetic activity – stars: merger

1. INTRODUCTION

The eruption of V838 Mon in 2002 (Brown 2002) and subsequent studies of its observed evolution (Munari et al. 2002; Kimeswenger et al. 2002; Crause et al. 2003; Kipper et al. 2004; Tylenda 2005), as well as, of other similar objects, i.e. V4332 Sgr (Martini et al. 1999; Tylenda et al., 2005) and M31 RV (Mould et al. 1990) have led to suggestions that these observed events were likely to be due to stellar mergers (Soker & Tylenda 2003, Tylenda & Soker 2006). Soker & Tylenda (2006), who termed these events mergebursts, discuss the different channels to produce a mergeburst.

For hours to months after merger the merger product is very luminous (e.g., Soker & Tylenda 2003; Bally & Zinnecker 2005; Tylenda 2005). For a grazing collision (namely, not

[1]Department of Physics, Technion-Israel Institute of Technology, 32000 Haifa, Israel; soker@physics.technion.ac.il.

[2]Department for Astrophysics, N.Copernicus Astronomical Center, Rabiańska 8, 87-100 Toruń, Poland; tylenda@ncac.torun.pl

a head on collision) an extended envelope is inflated by the merging stars. Still on a longer time scale, the mass loss process, both mass loss rate and geometry, is strongly influenced by the merger event (e.g. Morris & Podsiadlowski 2006). On a much later time of hundreds of years and longer, after the merger products reaches equilibrium, the process can alter the evolution of the star on the HR diagram (e.g., Podsiadlowski et al. 1990), like the formation of blue stragglers (e.g. De Marco et al. 2005; Sills et al. 2005).

In the present study we examine whether and when the merger product can become magnetically active, a process that might be observed in the X-ray and radio bands.

2. THE EXPECTED MAGNETIC ACTIVITY

2.1. The Rossby Number and X-ray Luminosity

The parameter that best indicates the level of magnetic activity of main sequence stars (e.g., Pizzolato et al. 2003), pre-main sequence stars (e.g., Preibisch et al. 2005), and subgiants (or G giants; e.g., Gondoin 2005) is the Rossby number

$$Ro \equiv \frac{P_{\rm rot}}{\tau_{c-b}} = \frac{P_{\rm rot}}{\alpha H_{p-c}/v_{c-b}}, \tag{1}$$

where $P_{\rm rot}$ is the rotation period of the star, $\tau_c = \alpha H_p/v_c$ is the convection overturn time, H_p is the pressure scale hight, αH_p is the mixing length, and v_c is the velocity of the convective cells. In particular, the correlations of some properties of the magnetic activity in main sequence stars with the Rosbby number and the explanation of these in the frame of the $\alpha\omega$ dynamo model are well established (e.g., Brandenburg et al. 1988; Saar & Brandenburg 1999). The subscript 'b' in equation (1) indicates that the value of τ_c is calculated at the bottom (inner boundary) of the envelope convective region, or just above it. In stars having a fully convective envelope, e.g., low mass main sequence stars, it is complicated to calculate τ_{c-b}. In that case one can define the global overturn time

$$\tau_{c-{\rm global}} \equiv \int_{R_b}^{R_*} \frac{dr}{v_c}, \tag{2}$$

where R_* is the stellar radius and R_b is the radius at the bottom of the envelope convective region. Kim & Demarque (1996) find for main sequence stars the relation $\tau_{c-b} \simeq 0.5\tau_{c-{\rm global}}$.

We are interested in the x-ray emission resulting from magnetic activity. The magnetic flux on the surface of magnetically active main sequence stars is proportional to the X-ray luminosity L_x (e.g., Pevtsov et al. 2003). The ratio of the X-ray luminosity to the bolometric luminosity of main sequence stars has a general relation of

$$\frac{L_x}{L_{\rm bol}} = C_x Ro^{-2}; \qquad 0.15 \lesssim Ro \lesssim 10. \tag{3}$$

$L_x/L_{\rm bol}$ saturates at a values of $\sim 10^{-3}$ for $Ro \lesssim 0.15$, while no activity is detected for $Ro \gtrsim 10$ (Pizzolato et al. 2003). For main sequence stars $C_x \simeq 10^{-5}$ (Pizzolato et al. 2003), while for G giants (subgiants) $C_x \sim 10^{-6}$ (Gondoin 2005). YSOs are usually in the saturated regime, and show higher activity than main sequence stars with the same mass or bolometric luminosity (Preibisch et al. 2005).

2.2. The Rossby Number in Inflated Merger Products

Following Tylenda & Soker (2006) we assume that the merger remnant is composed of a more or less undisturbed pre-merger primary star of mass, M_1, and radius, R_1, surrounded be an envelope of mass, $M_{\rm env}$, inflated up to an outer radius, $R_{\rm env}$.

Merger products are expected to contract more or less along the Hayashi line (Tylenda 2005; Tylenda & Soker 2006). However, they are different from young stellar objects (YSOs) contracting along the Hayashi line. An inflated merger product has a well defined and relaxed central region−the pre-merger primary star, while the contracting envelope contains a relatively small amount of mass.

In that respect, the inflated merger remnants are more similar to late asymptotic giant branch (AGB) and post-AGB stars; both classes of objects share the following properties:

1. Radius of tens to hundreds solar radii.
2. Luminosity of $\sim 3 \times 10^3 - 10^5 L_\odot$.
3. Cool envelope, $T_{\rm eff} < 10^4$ K.
4. Extended convection region in the envelope. To compensate for the low density in the expression for convective energy transport, the convective velocity must be large.
5. A low mass envelope with a compact massive center: the stellar core in late AGB stars and post AGB stars, and the primary in inflated merger products.

Based on these properties, we proceed as follows. To estimate the convective velocity v_c we use results of late AGB and post-AGB stars (Soker & Harpaz 1992; 1999). These results show that just below the photosphere, where the temperature is $T \sim 10^4$ K, the convection velocity is $v_c \sim 8$ km s^{-1}. In the stellar numerical code the convection velocity is limited by the isothermal sound speed, because for higher convection velocities the dissipation is large, and the convective cells rapidly slow down. The value of v_c stays at $v_c \simeq 8 - 20$ km s^{-1} in most of the envelope. We will therefore take $v_c = 10$ km s^{-1}, and use the global convective overturn time as defined in equation (2). Using $\tau_{c-b} \simeq 0.5\tau_{c-\mathrm{global}}$ (Kim & Demarque 1996), and $R_b \ll R_*$, we take for merger remnants

$$\tau_{c-m} \simeq 0.5\frac{R_{\mathrm{env}}}{v_c} \simeq 40\frac{R_{\mathrm{env}}}{100R_\odot}\mathrm{days}. \tag{4}$$

A similar result is obtained if we consider, following Tylenda (2005), the envelope of the merger product to be an $n = 3/2$ polytrope, and calculate τ_c at the middle of the envelope $R = R_{\mathrm{env}}/2$. In an $n = 3/2$ envelope the pressure scale hight has its maximum value of $H_p \simeq R_{\mathrm{env}}/10$ at the middle of the envelope. Taking for the ratio of mixing length to pressure scale hight $\alpha = 1.86$ (Kim & Demarque 1996) would give $\tau_{c-m} \simeq 15(R_{\mathrm{env}}/100R_\odot)$ days. On the other hand, our estimate of v_c might be too large, with an underestimate of τ_c, as pre-main sequence stars have $\tau_c \simeq 200$ day (Preibisch et al. 2005).

The inflated envelope of the merger remnant stores an angular momentum comparable to that of the pre-merger orbital motion of the secondary. For an $n = 3/2$ polytropic envelope having $R_{\mathrm{env}} \gg R_1$ the moment of inertia can be approximated as $I \simeq 0.11M_{\mathrm{env}}R^2_{\mathrm{env}}$. We assume that after several dynamical time scales the convection in the envelope brings the envelope to a solid body rotation. Assuming that the secondary had a Keplerian velocity as it collided with the primary at radius R_1 and that the merger product envelope has a mass comparable to that of the secondary, we can estimate a rotation period of the envelope as

$$P_{\mathrm{rot}} \simeq 130\left(\frac{R_{\mathrm{env}}}{100R_\odot}\right)^2\left(\frac{M_1}{M_\odot}\right)^{-1/2}\left(\frac{R_1}{R_\odot}\right)^{-1/2}\mathrm{days}. \tag{5}$$

Equivalently we can define a parameter η being the ratio of the envelope rotation velocity to the Keplerian velocity v_{Kep}(or Keplerian period P_{Kep} to rotation period) at R_{env}, namely

$$\eta \equiv \left(\frac{v_{\mathrm{rot}}}{v_{\mathrm{Kep}}}\right)_{R_{\mathrm{env}}} \simeq 0.9\left(\frac{100R_1}{R_{\mathrm{env}}}\right)^{1/2}. \tag{6}$$

The second equality uses equation (5).

As it is clear from the above equations, when the remnant contracts, it spins-up. We assume that after it reaches a rotation velocity of some fraction η_{max} of its break-up (Keplerian) velocity mass loss keeps the value of η unchanged. When it happens, the rotation period is

$$P_{\mathrm{rot}} \simeq 230\left(\frac{\eta_{\mathrm{max}}}{0.5}\right)^{-1}\left(\frac{R_{\mathrm{env}}}{100R_\odot}\right)^{3/2}\left(\frac{M_1}{M_\odot}\right)^{-1/2}\mathrm{days}, \tag{7}$$

The Rossby number (eq. 1) for the inflated merger remnant can be obtained from equation (4) using equations (5) or (7), i.e.

$$Ro(\text{merger}) \simeq 3 \left(\frac{R_{\rm env}}{100R_\odot}\right) \left(\frac{M_1}{M_\odot}\right)^{-1/2} \left(\frac{R_1}{R_\odot}\right)^{-1/2} \tag{8}$$

if equation (6) gives $\eta < \eta_{\rm max}$ or

$$Ro(\text{merger}) \simeq 6 \left(\frac{\eta_{\rm max}}{0.5}\right)^{-1} \left(\frac{R_{\rm env}}{100R_\odot}\right)^{1/2} \left(\frac{M_1}{M_\odot}\right)^{-1/2}. \tag{9}$$

otherwise.

2.3. The X-Ray Luminosity of Inflated Merger Products

As the merger products are somewhat similar to giant stars, we should take $C_x = 10^{-6}$ in equation (3) (Gondoin 2005). The operation of an $\alpha\omega$ dynamo in the envelope of AGB stars that were spun-up by low mass companions spiraling inside their envelope was considered before (Nordhaus & Blackman 2006 and references therein). However, AGB stars that are expected to rotate very slowly and have large Rossby number $Ro \gg 10$ (Soker & Zoabi 2002), do amplify magnetic fields, as evidenced by polarization of maser emission in local regions around these stars (Szymczak 1998; Vlemmings 2005). In seems as if a dynamo based mainly on convection, and not on convection+rotation (the $\alpha\Omega$ dynamo model), can also amplify magnetic fields in giants (Soker & Zoabi 2002; Soker & Kastner 2003; Dorch 2004), but not as efficiently as the $\alpha\omega$ dynamo we appeal to here. Therefore, although our envelope model is similar to that of AGB stars, the dynamo model we use is much more efficient than that expected in AGB stars. By taking $C_x = 10^{-6}$ we might underestimate the X-ray luminosity of merger remnants. Using equation (8) or (9) in equation (3) with $C_x = 10^{-6}$ we find the expected X-ray luminosity of the contracting envelope

$$L_x \simeq 4 \times 10^{30} \left(\frac{R_{\rm env}}{100R_\odot}\right)^{-2} \left(\frac{M_1}{M_\odot}\right) \left(\frac{R_1}{R_\odot}\right) \left(\frac{L_{\rm bol}}{10^4 L_\odot}\right) \text{ erg s}^{-1}, \tag{10}$$

if equation (6) gives $\eta < \eta_{\rm max}$, or

$$L_x \simeq 1.2 \times 10^{30} \left(\frac{\eta_{\rm max}}{0.5}\right)^{2} \left(\frac{R_{\rm env}}{100R_\odot}\right)^{-1} \left(\frac{M_1}{M_\odot}\right) \left(\frac{L_{\rm bol}}{10^4 L_\odot}\right) \text{ erg s}^{-1}, \tag{11}$$

otherwise.

3. RESULTS FOR V838 Mon

We can apply the general derivation of the previous section to predict the expected evolution of the X-ray luminosity of V838 Mon.

As discussed in Tylenda (2005) the observed decline in flux of V838 Mon after its eruption can be well described by gravitational contraction of a low-mass inflated envelope sitting on top of an early B-type main sequence star. Assuming more recent determinations of the distance to V838 Mon giving a value of ~ 6 kpc (Sparks et al. 2007; Bond & Afsar 2007) (compared to 8 kpc assumed in Tylenda 2005) the parameters of the model fitted to the observed decline become: $M_1 \simeq 7M_\odot$, $R_1 \simeq 3.5R_\odot$ and $M_{\rm env} \simeq 0.12M_\odot$. At the beginning of the contraction (August-September 2002) the envelope radius was $R_{\rm env} \simeq 2000R_\odot$. Using the same approach as in Tylenda (2005) and the above parameters, we can follow the contraction of the V838 Mon remnant to obtain the evolution of $R_{\rm env}$ and $L_{\rm bol}$ with time. This allows us to predict from the relations derived in Section 2 the evolution of the X-ray luminosity. The results are presented in Fig. 1. The curves show the evolution of the X-ray luminosity with time and are labelled with the value of $\eta_{\rm max}$ used when caluculating the luminosity from equations (10) and (11). The rising parts of the two upper curves correspond to the initial, constant angular momentum phase of the remnant contraction ($\eta < \eta_{\rm max}$). The declining parts show the phase when the envelope is loosing angular momentum via mass loss so that the condition $\eta = \eta_{\rm max}$ is kept. The dotted parts of the curves show the periods when the Rossby number is greater then 5. We expect that during this period the dynamo is less effective than assumed in our estimates so our results may overestimate the X-ray luminosity.

With *Chandra* 23 hours of observations of the Orion Nebula, at a distance of 0.45 kpc, Feigelson et al. (2002) could detect sources with luminosity down to $L_x = 10^{28}$ erg s^{-1}. For a distance of 6 kpc to V838 Mon (Sparks et al. 2007; Bond & Afsar 2007), and with a similarly long observation, we expect to detect any emission if $L_x \gtrsim 2 \times 10^{30}$ erg s^{-1}. We conservatively took $C_x = 10^{-6}$ in equation (3), as appropriate for subgiants (Gondoin 2005) rather than $C_x = 10^{-5}$ as appropriate for main sequence stars (Pizzolato et al. 2003). More than that, bright pre main sequence stars with no accretion disk are X-ray brighter than those with disks (Preibisch et al. 2005). As V838 Mon does not have an accretion disk, it is quite possible that we underestimate the X-ray luminosity of merger products in equations (10) and (11) by up to an order of magnitude. Therefore, it is quite possible that 10 hours of XMM-Newton or *Chandra* observation could detect X-rays from V838 Mon at present and in coming years.

V838 Mon was observed with *Chandra* for 6800 s a year after its outburst by Orio et al. (2003) who were able to put only an upper limit of $F_X \leq 6.5 \times 10^{-14} {\rm erg\,cm^{-2}\,s^{-1}}$. With

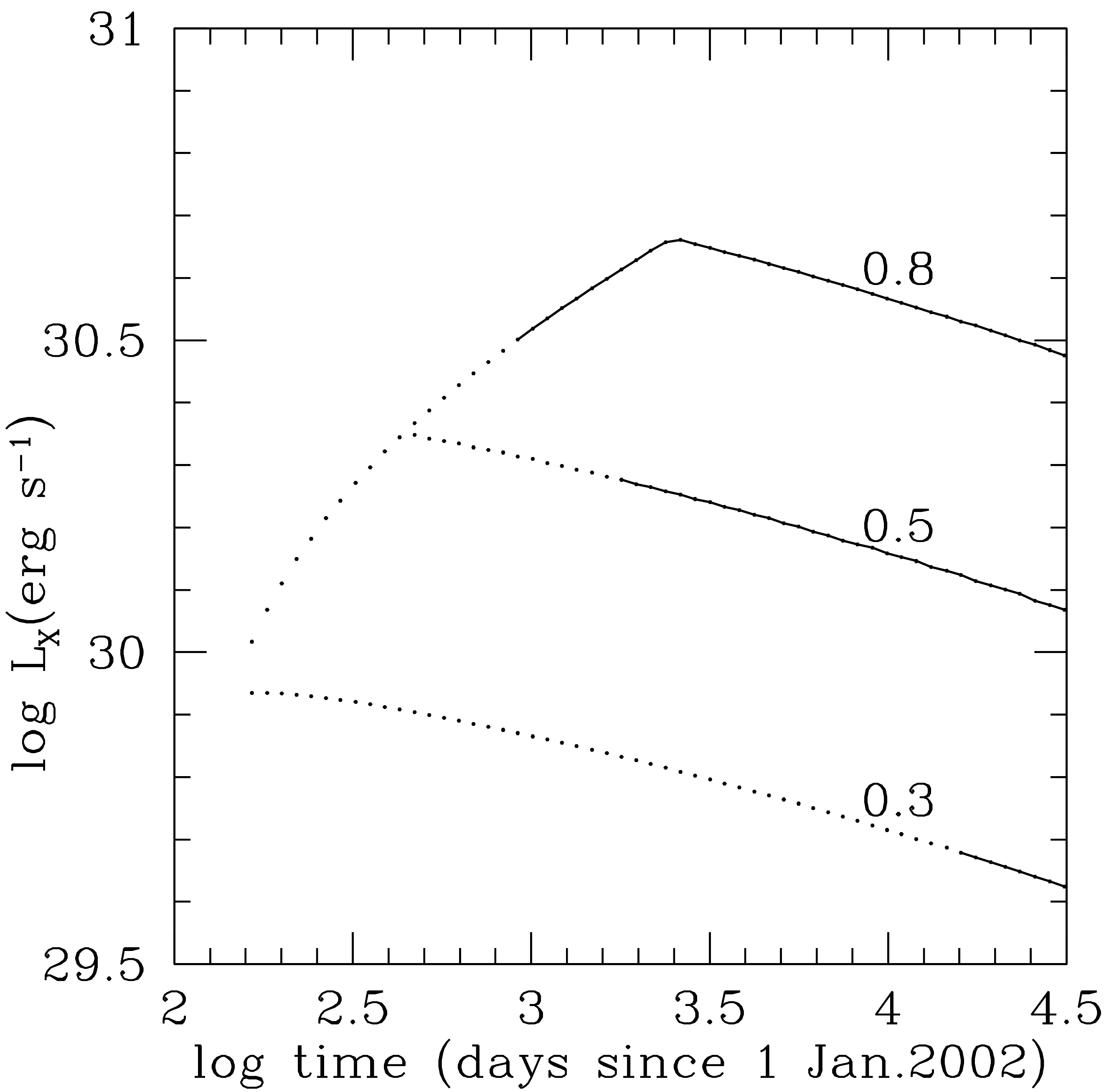

Fig. 1.— The expected evolution of the X-ray luminosity from the magnetically active V838 Mon remnant according to the merger model. The curves are labelled with the value of $\eta_{\max}$, the maximum ratio of rotation velocity to Keplerian velocity on the equator. Dotted parts indicate the time period when the Rossby number is $Ro > 5$, where the $\alpha\omega$ dynamo model is less efficient.

a distance of ~ 6 kpc this corresponds to $L_X \leq 2.8 \times 10^{32} \mathrm{erg\,s^{-1}}$ which is well above our predictions.

4. SUMMARY

According to the stellar merger model of the V838 Mon outburst and similar merger products (which we term mergebursts), a large envelope is formed around the more massive of the two merging stars. The envelope then contracts on a thermal time scale. The merger remnant should become a fast rotator as it contracts. As the remnant contracts more or less along the Hayshi line, its envelope possesses a large convective region. The fast rotation and the envelope convection are the two ingredients required in the $\alpha\omega$ dynamo model−a successful model for magnetic activity of main sequence stars, pre-main sequence stars, and subgiants.

We applied the $\alpha\omega$ model to contracting merger products by using the Rossby number (eq. 1), and the relation between the Rossby number and X-ray luminosity known for magnetically active stars, scaled according to the expression for subgiant (or G giant) stars (eq. 3). We also assumed that after the contracting product reaches some fraction $\eta_{\max}$ of its break-up (Keplerian) velocity, this ratio does not increase any more, because a stellar wind removes angular momentum from the envelope. Our final (and conservative) prediction for the X-ray luminosity of magnetically active merger products are given by equation (10) for merger products before they reach our assumed maximum rotation rate, and by equation (11) for merger products rotating at $\eta_{\max}$.

In section 3 we apply the results to our model of V838 Mon. The results are presented in Fig. 1 for three values of the assumed maximum rotating rate $\eta_{\max}$, as marked near the lines. For too large Rossby numbers $Ro \gtrsim 10$ (Pizzolato et al. 2003; we here take a stronger constraint of $Ro \gtrsim 5$) of the $\alpha\omega$ dynamo is not efficient any more. The dotted lines are the evolutionary stages where the expected Rossby number of V838 Mon is $Ro > 5$, and we expect no strong magnetic activity.

¿From Fig. 1 we learn the following.

1. There is no magnetic activity at the first several years, and hence no X-ray emission is expected. The observation by Orio et al. (2003) was made a year after the outburst, when no magnetic activity and no X-ray emission is expected.

2. For a reasonable values of maximum rotation rate $0.4 \lesssim \eta_{\max} \lesssim 0.8$, V838 Mon will reach a maximum activity at 6-8 years after outburst. The expected X-ray luminosity

then slowly declines.

3. The X-ray luminosity in the coming years will be $L_x \sim 3 \times 10^{30}$ erg s^{-1}. At the distance of V838 Mon the expected X-ray flux is $F_X \sim 6 \times 10^{-16}$erg cm^{-2} s^{-1}. We estimate that with 100,000 seconds of observation this emission can be detected.

We therefore highly encourage 100,000 seconds of X-ray observation of V838 Mon in 2008. Even if no X-ray is detected, the results is of some importance, as it can strongly constrain models for V838 Mon, e.g., rules out accreting white dwarf. Orio et al. (2003) noted that their null detection rules our a symbiotic-like event to the V838 Mon outburst.

We point out that the null detection of X-ray emission from two AGB stars (Kastner & Soker 2004) is not directly relevant to the case of V838 Mon. First, and most important, our prediction is based on the $\alpha\omega$ dynamo model, namely, the amplification of the magnetic field by the operation of both rotation and convection, which is known to be very efficient. On the other hand, predictions for AGB stars are based on the amplification of the magnetic field by convection alone (Soker & Zoabi 2002), which is thought to be much less efficient. Second, V838 Mon is an order of magnitude more massive than an upper AGB star. We predict the magnetic activity to take place when the radius, luminosity and temperature of V838 Mon is similar to that of upper AGB star. Due to the higher mass we expect the mass loss rate to be smaller, and the wind speed to be faster. Therefore, the column density to the expected X-ray emitting region will be much lower.

Finally, the magnetic fields might be detected also in masers spots. Deguchi (2005) and Claussen (2005) report the detection of SiO maser around v838 Mon. We predict that if maser emission, in SiO, H_2O, or OH, will be observed from 2007, some regions might show polarization indicating the presence of magnetic fields, similar to the case around AGB stars, e.g., Vlemmings et al. (2005).

We thank an anonymous referee for useful comments. This research was supported in part by the Asher Fund for Space Research at the Technion, as well as, from the Polish State Committee for Scientific Research grant no. 2 P03D 002 25.

REFERENCES

Bally, J., & Zinnecker, H. 2005, AJ, 129, 2281

Bond, H. E. & Afsar, M. 2007, in ASP Conf. Ser., The Nature of V838 Mon and its Light Echo, ed. R.L.M. Corradi & U. Munari (San Francisco: ASP) (astro-ph/0608220)

Brandenburg, A., Saar, S. H., & Turpin, C. R. 1998, ApJ, 498, L51

Brown, N. J. 2002, IAU Circ., 7785

Claussen, M. J., Healy, K. R., Starrfield, S., & Bond, H. E. 2005, AAS, 207, 182.12

Crause, L. A., Lawson, W. A., Kilkenny, D., et al. 2003, MNRAS, 341, 785

Deguchi, S., Matsunaga, N., & Fukushi, H. 2005, PASJ, 57, L25

De Marco, O., Shara, M. M., Zurek, D.; Ouellette, J. A.; Lanz,T., Saffer, R. A. & Sepinsky, J. F. 2005, ApJ, 632, 894

Dorch, S. B. F. 2004, A&A, 423, 1101

Feigelson, E. D., Broos, P., Gaffney, J. A., III, Garmire, G., Hillenbrand, L. A., Pravdo, S. H., Townsley, L., & Tsuboi, Y. 2002, ApJ, 574, 258

Gondoin, P. 2005, A&A, 444, 531

Kastner, J. H. & Soker, N. 2004, ApJ, 608, 978

Kim, Y.-C. & Demarque, Y. 1996, ApJ, 457, 340

Kimeswenger, S., Lederle, C., Schmeja, S., Armsdorfer, B. 2002, MNRAS, 336, L43

Kipper, T., Klochkova, V. G., Annuk, K., et al. 2004, A&A, 416, 1107

Martini, P., Wagner, R. M., Tomaney, A., et al. 1999, AJ, 118, 1034

Morris, T. & Podsiadlowski, Ph. 2006, MNRAS, 365, 2

Mould, J., Cohen, J., Graham, J. R., et al. 1990, ApJ, 353, L35

Munari, U., Henden, A., Kiyota, S., et al. 2002, A&A, 389, L51

Nordhaus, J., & Blackman, E. G. 2006, MNRAS, 370, 2004

Orio, M., Starrfield, S. G. & Tepedenlegliolu, E. 2003, IAU Circ. 8110

Pevtsov, A. A., Fisher, G. H., Acton, L. W., Longcope, D. W., Johns-Krull, C. M., Kankelborg, C. C., & Metcalf, T. R. 2003, ApJ, 598, 1387

Pizzolato, N., Maggio, A., Micela, G., Sciortino, S., & Ventura, P. 2003, A&A, 397, 147

Podsiadlowski, P., Joss, P. C., & Rappaport, S. 1990, A&A, 227, L9

Preibisch, T. et al. 2005, ApJ Supp. 160, 401

Saar, S. H., & Brandenburg, A. 1999, ApJ, 524, 295

Sills, A., Adams, Tim, & Davies, M. B. 2005, MNRAS, 358, 716

Soker, N. & Harpaz, A. 1999, MNRAS, 310, 1158

Soker, N. & Harpaz, A. 1992, PASP, 104, 923

Soker, N. & Kastner, J. H. 2003, ApJ, 592, 498S

Soker, N. & Tylenda, R. 2003, ApJ, 582, L105

Soker, N. & Tylenda, R. 2006, MNRAS, in press

Soker, N. & Zoabi, E., 2002, MNRAS, 329, 204

Sparks, W. B. et al. 2007, in ASP Conf. Ser., The Nature of V838 Mon and its Light Echo, ed. R.L.M. Corradi & U. Munari (San Francisco:ASP), in press

Szymczak, M., Cohen, R. J., & Richards, A. M. S. 1998, MNRAS, 297, 1151

Tylenda, R., 2005, A&A, 436, 1009

Tylenda, R., Crause, L., Górny, S.K., & Schmidt, M. 2005, A&A, 439, 651

Tylenda, R., & Soker, N. 2006, A&A, 451, 223

Vlemmings, W. H. T., van Langevelde, H. J., Diamond, P. J. 2005, A&A, 434, 1029